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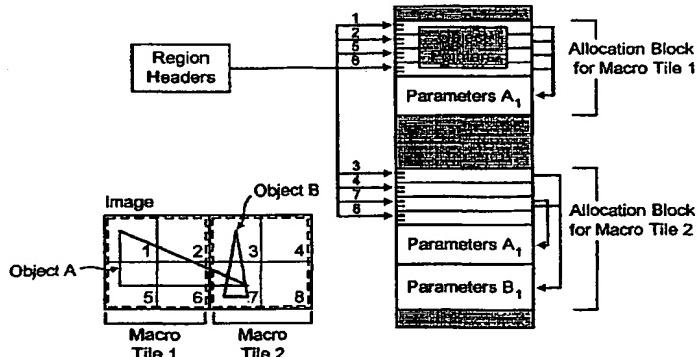
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(54) Title: TILING AND COMPRESSION FOR RENDERING 3D IMAGES



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(57) **Abstract:** A 3-dimensional computer generated image is generated by subdividing the image into a plurality of rectangular areas. Object data for each rectangular area is loaded into a display list memory (4) until that memory is substantially full. Image data and shading data for each picture element of each rectangular area is derived by an image synthesis processor (6) from the object data. Image data is then stored in a local memory (16) and further object data loaded into the display list memory (4) and replaces the existing contents. Once this has happened, the stored image data and shading data is retrieved and additional image data and shading data derived for each picture element by the image synthesis processor (6) using the new object data and the previously derived image and shading data. When there is no further object data to load to the display list memory the shading data is provided for display for the rectangular areas by a frame buffer (11). The memory may be managed by allocating at least one block of storage from the display list memory to each rectangular area and then storing in that block of memory, data which pertains to surfaces which intersect that rectangular area. A determination is made as to when a predetermined number of blocks have been used for a rectangular area. When this number is reached, the system starts to derive shading data for the rectangular areas, thereby releasing blocks of storage to be allocated to further rectangular areas in the display list memory.



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TILING AND COMPRESSION FOR RENDERING 3D IMAGES

This invention relates to memory management for use  
with systems for generating 3-dimensional computer  
5 generated images.

In our British Patent No. 2281682, there is described  
a 3-D rendering system for polygons in which each object  
is seen to be viewed as defined in a set of surfaces which  
are infinite. Each elementary area of the screen in which  
10 an image is to be displayed has a ray projected through it  
from a viewpoint into the 3-dimensional scene. The  
location of the intersection of the projected ray with  
each surface is then determined. From these  
intersections, it is then possible to determine whether  
15 any intersected surface is visible at that elementary  
area. The elementary area is then shaded for display in  
dependence on the results of the determination.

The system can be implemented in a pipeline type  
processor comprising a number of cells, each of which can  
20 perform an intersection calculation with a surface. Thus,  
a large number of surface intersections can be computed  
simultaneously. Each cell is loaded with a set of co-  
efficients defining the surface for which it is to perform  
the intersection test.

25 A further improvement is described in our UK Patent  
Application No. 2298111. In this, the image plane is  
subdivided into sub-regions or tiles such that tiles can  
be processed in turn. It is proposed to use a variable  
tile size and to project a bounding box around complex  
30 objects so that only those tiles falling within the  
bounding box require processing. This is done by firstly  
determining the distribution of objects on the visible  
screen in order for a suitable tile size to be selected.  
The surfaces which define the various objects are then  
35 stored in a list, known as the display list, thereby

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avoiding the need to store identical surfaces for each tile, since one object made of many surfaces could appear in a number of tiles. Object pointers which identify the objects in the display list are also stored. There is one  
5 object pointer list per tile. The tiles can then be rendered in turn using the ray casting technique described above until all objects within each tile are processed. This is a useful method because no effort needs to be made to render objects which are known not to be visible in a  
10 particular tile.

A further improvement on this is proposed in our International Patent Application No. PCT/GB99/03707, in which any tiles within the bounding box which are not required to display a particular object are discarded  
15 before rendering.

A block diagram of the type of processor used is shown in Figure 1. This comprises a tile accelerator unit 2 which performs the tiling operations referred to above and supplies the tile information to a display list memory 4. This in turn supplies tile object data for processing to the image synthesis processor (ISP) 6 which performs the ray/surface intersection tests referred to above. This derives image data which comprises object identification and depth data. After this, the thus derived image data  
20 is supplied to a texturing and shading processor (TSP) 8 which applies texturing and shading data to surfaces which have been determined as visible and outputs image shading data to a frame store.  
25

Most 3-D graphic systems use what is known as immediate mode rendering. This type of rendering avoids the needs to store a copy of the entire scene in the display list memory. Instead, each polygon is rendered the moment that it is presented to the rendering hardware. This has the advantage of avoiding the storage  
30 requirements of the display list memory. However, it also precludes the considerable optimisation which are possible  
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with the type of rendering described in our British Patent No. 2281682 and improved on in our British Patent Application No. 2298111. Advantages such as deferred texturing and translucency sorting are possible using this  
5 type of architecture.

The complexity of scenes which it is necessary to render using 3-D graphic systems is increasing as hardware becomes more powerful. However, this presents a problem for display list based renderers because the display list  
10 storage requirements also increase. In the past, if the display list memory became exhausted, parts of the scene would simply not be rendered. Image corruption of this sort is no longer considered acceptable. The cost of memory, which is not falling as fast as scene complexity  
15 is rising, makes increasing the amount of memory in the system unfeasible.

Preferred embodiments of the present invention provide a method of managing the display list in such a manner as to impose an upper bound on the memory  
20 consumption, whilst at the same time attempting to minimise the memory bandwidth consumed by the system. This may be achieved by storing the state of the system (ISP and TSP) to memory before rendering of a tile is complete, and reloading this state at a later time in  
25 order to finish the rendering. We refer to this technique as "z/frame buffer load and store".

In a preferred embodiment, this screen is divided up into a number of regions called macro-tiles, in which each of these consists of a rectangular region of the screen composed of a number of smaller tiles. Memory in the display list is then divided into blocks and these are listed in a free store list. Blocks from the free store are then allocated to the macro-tiles as required. The tiling operation stores polygon parameter data and object  
30 pointers for surfaces in each block associated with each macro-tile in which they are visible. When the memory for  
35

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the parameters fills up, or reaches some predefined threshold, the system selects a macro-tile, performs a z/frame buffer load, and renders the contents of the macro-tile before saving it using a z/frame buffer store operation. Upon completion of such a render, the system frees any memory blocks associated with that macro-tile, thereby making them available for further parameter storage. The z/frame buffer load and store operations are restricted to the macro-tiles that are actually rendered rather than every tile on the screen as was previously the case. Tiling of either the remainder of the current frame or of the next frame to be displayed then continues in parallel with macro-tile renders and the allocation of blocks of memory from the same pool to further macro-tiles. It is not necessary to provide any double buffering of the parameter list and thus the memory requirements of the system are further reduced.

The invention is defined with more precision in the appended claims to which reference should now be made.

Preferred embodiments of the invention will now be described in detail by way of example with reference to the accompanying drawings in which:

**Figure 1** shows a schematic diagram of the rendering and texturing system referred to above;

**Figure 2** shows schematically how the display list is ordered in a known tiling system;

**Figure 3** shows how the display list is ordered in accordance with the macro-tiling embodying the invention;

**Figure 4a, b, and c** show alternative arrangements for the allocation of data in blocks in the display list in accordance with an embodiment of the invention;

**Figure 5** shows a further embodiment of the display list;

**Figure 6** shows schematically the z depths for four polygons and z compression by storage of plane parameters for the four polygons;

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**Figure 7** shows graphically the results of run-length encoding.

5       **Figure 8** shows a block diagram of an example of the type of rendering system with which the present invention may be used;

**Figure 9** shows the system of figure 8 in an embodiment of one aspect of the present invention;

**Figure 10** is a flow chart illustrating the memory management used by an embodiment of the invention;

10      **Figure 11** is a flow chart for sub-process of the flow chart figure 10; and

**Figure 12** is a block diagram of the tile accelerator used in the embodiment of the invention.

15      In the system of Figure 1, polygons which are to be displayed are broken down into planar triangles. The data representing these is transformed by either hardware or software into a screen space representation and is then stored in local memory. The tiling process then performed by the tile accelerator 2 creates a list of pointers to the transformed triangle data for each tile in the scene. This is then stored in the display list along with parameters pertaining to the object of which the triangle is a portion. This is shown schematically in Figure 2 in which the region headers 10 correspond to the identities 20 of the tiles 1-8 shown in the Figure. As can be seen, the tiles cover two triangles named object A and object B. Object A is visible in tiles 1, 2, 5, 6 and 7 and object B is visible in tiles 3 and 7.

30      A display list 12 receives from the tile data for the objects visible in each tile and links are provided to the parameters associated with each object, namely parameters A and parameters B in this example. Thus, it can be seen that the object pointers for tiles 1, 2, 5, 6 and 7 point to parameters A and the object pointers for tiles 3 and 7 point to parameters B. When this data is fed to the image 35

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synthesis processor 6 and texturing and shading processor 8, the correct image data will be applied to the pixels of each tile.

If the image is complex in relation to the size of  
5 the display list it may not be possible to store all the  
tile data in the display list simultaneously and technique  
which is referred to as z/frame buffer load and store is  
used. Therefore, the display list will be loaded with  
data by the tile accelerator for all the tiles until it is  
10 substantially full. This will only represent a portion of  
the image data. This data is then rendered by the ISP and  
TSP and the result stored in local memory. This is called  
a partial render. The image is rendered one tile at a  
time in the normal way. After rendering of each tile, the  
15 internal state of the ISP (containing z, stencil and  
object address information) is written out to external  
memory and image data from the TSP is written to the frame  
buffer. These two operations together comprise a z/frame  
buffer store. At the end of partial render, a render and  
20 a z frame buffer store operation has occurred for each  
tile on the screen.

At this point, the first part of the display list is  
discarded (as this data has been used for rendering the  
tile), and the memory is used to receive further output  
25 from the tile accelerator. When the display list memory  
fills up again, or when the tile accelerator reaches the  
end of the scene data, another partial render occurs. As  
processing begins for each tile in turn, the previously  
stored ISP data information is reloaded from external  
30 memory and, if necessary, for the blending operations to  
be performed, the image data from the frame buffer is  
loaded into the TSP. This is the z/frame buffer load  
operation. The next portion of the display list can then  
be rendered in that tile as if it had never been  
35 interrupted. Finally, after the tile is rendered, a  
z/frame buffer store will save the necessary data

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information to allow another cycle of partial renders to occur.

By working in this way, it is possible to render a scene of great complexity whilst using only a limited  
5 amount of memory.

Figure 3 shows how the memory of the display list is allocated in an embodiment of the invention. It can be seen in Figure 3 that the image portion shown in Figure 1 is, in this instance, divided into two macro-tiles headed  
10 macro-tile 1 and macro-tile 2. The display list is divided into two portions, the first portion being for macro-tile 1 and the second portion for macro-tile 2. The region headers for the tiles in macro-tile 1 all feed into the object pointers for macro-tile 1. As only object A is  
15 visible in macro-tile 1, only parameters A<sub>1</sub> need to be stored in this memory block. Thus, it can be seen that the object pointers for tiles 1, 2, 5 and 6 all point into parameters A<sub>1</sub>.

In macro-tile 2 both object A and object B are  
20 visible, both being present in tile 7. Thus, parameters A<sub>2</sub> and parameters B<sub>2</sub> have to be stored in the memory block allocation for macro-tile 2. Thus it can be seen that the object pointer for tile 7 points to parameters A<sub>2</sub> and parameters B<sub>2</sub> whilst the object pointer for tile 3 points  
25 only to parameters B<sub>2</sub>.

The size of macro-tiles can be predetermined or a system can be implemented which defines the size of macro-tiles in dependence on the complexity of the scene. The macro-tiling process will be performed downstream of the  
30 basic tiling operation by the tiling accelerator 2.

The memory available in the display list storage is first divided into allocation blocks ("blocks") and the address of each block is stored in a FIFO or stack known as the free store. The choice of block sizes is a  
35 compromise between space wastage with large blocks and the storage requirements involved in managing a large number

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of smaller blocks. It is also influenced by the properties of the memory technology being used.

After this, the screen which has already been divided up into tiles is then divided into macro-tiles. In their 5 simplest form, all macro-tiles on the screen are the same size which could correspond at its smallest to a single tile. In the example given in Figure 3, a macro-tile size  $2 \times 2$  is used for simplicity of illustration, although in practice the size is likely to be larger.

Initially, all allocation blocks are in the free store (not illustrated). The tiling accelerator identifies a set of tiles (and macro-tiles) that a particular object, e.g., a triangle, intersects. Then, for each macro-tile, in turn, when the first object data 15 that crosses the macro-tile is identified, a block from the free store is claimed and becomes associated with that macro-tile. Object data is then stored in that block. Further blocks are claimed from the free store when there is insufficient space in the current blocks to store a 20 piece of data.

Once a macro-tile has been rendered by the image synthesis processor 6 and texturing and shading processor 8, the memory block associated with it can be returned to the free store. In order to do this, blocks need somehow 25 to be linked to the macro-tile with which they are associated. One possibility to implement this is to use a word in each allocation block to create a linked list of blocks. Alternatively, rather than adding and removing allocation blocks from the free store list, they can be 30 marked as used or unused *in situ*, with links between used blocks created within the free store structure.

As explained above, the tile accelerator is used to generate a set of tiles and strip mask information for a strip of triangles in the usual way. Additionally, it 35 determines which macro-tiles the strip falls into. The tiling accelerator 2 then writes parameter data in

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independent lists for each macro-tile in which the strip is visible. This parameter data is written to the display list in the appropriate place for each macro-tile.

Clearly, some duplication of data will arise. However,  
5 this allows all the memory associated with a particular macro-tile to be released after that macro-tile has been rendered without affecting the display lists of other macro-tiles.

At the beginning of the first frame of image data to  
10 be displayed, tiling begins. Object pointers for the objects visible in each macro-tile are produced and written to a block from the display list allocated to that macro-tile along with the relevant object parameters for each object visible in that macro-tile. This process  
15 continues until the display list is substantially full or some threshold has been exceeded, e.g., 75% of the allocation blocks have been used. When this triggering level is reached, the system selects a macro-tile and begins to render it into the frame buffer using the image  
20 synthesis processor and the texture and shading processor. The manner in which the macro-tile is selected is discussed in more detail below. The decision may depend on a number of factors. Typically the macro-tile that currently uses the largest number of allocation blocks  
25 will be selected since this frees up the maximum amount of memory for new data. Tiling continues in parallel with rendering for the remainder of data for the first frame. The 75% threshold is used because this leaves sufficient unused memory to be allocated by the continuing tiling  
30 process whilst other memory is rendered and subsequently returned to the free store. So that tiling can be performed into the macro-tile which is being rendered, its region header (the pointer to the macro-tile's pointer lists and allocation block(s)) is exchanged for a pointer  
35 to an empty tile. Rendering can then continue for the data for the previous macro-tile and the tiling

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accelerator can write data into the new allocation block for the empty one. When the rendering of a macro-tile is complete, its allocation blocks are returned to the free store. Then, provided that the memory use is above 5 threshold value, another macro-tile is chosen and another rendering operation begins. The 75% threshold is an adjustable parameter. This is because the ISP and TSP can perform operations such as deferred texturing more efficiently when a larger part of the display list is in 10 memory (and most efficiently when the whole list is in memory). The threshold is adjustable to enable a balance to be found between the conflicting requirements of large display list size, and adequate space into which to tile the remainder of the scene.

15       When tiling of a frame of image data is complete, the system can then begin to tile the next frame, even while the rendering of the previous frame is still in progress. The allocation blocks associated with macro-tiles from the new frame must be distinct from those associated with 20 macro-tiles from the previous frame. This can be achieved by maintaining a second set of blocks independent of those used by the previous frame. This would be achieved by maintaining independently a second set of region headers. Allocation blocks are taken from the same free store for 25 all frames, which means that it is not necessary to double the size of the display list. This gives a further saving in memory usage.

Thus, it can be seen that the z/frame buffer load and 30 store processes occur at the beginning and end of each render respectively. They only take place with the tiles in a macro-tile that has been rendered. There is no need for a load operation before the first rendering and no need for a store after the last rendering. It can be seen that the efficiency and memory usage arises from rendering 35 a macro-tile into the frame buffer when the number of allocation blocks used reaches some predefined threshold

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and that upon completion of such a render, the memory blocks associated with the macro-tile rendered are freed up, making them available for further parameter storage.

The object parameters which are stored are typically coordinates of triangles where these are the objects being rendered, object colours, etc. As can be seen, both object parameters such as these and object pointers are stored in the allocation block for each macro-tile. This allows parameters and pointers to be discarded easily when they are no longer required. The proximity of parameter and pointer data in the memory can lead to a significant reduction in the number of page breaks in the memory system if sufficiently small allocation blocks or an appropriate layout with larger blocks is used. Page breaks reduce the performance of the memory system and are caused when consecutive accesses to the memory hardware are not within the same page. The storage of object pointers and parameter data within the same page wherever possible is an effective way to minimise these page breaks.

Various schemes from layouts of pointers and parameters within the allocation block are possible. Some examples are shown in Figure 4a, b and c. The simplest schemes allocate pointers in small pointer blocks at the head of the allocation block to optimise reading and writing. The last pointer in the block is a link to the next pointer block where a linked list is required. In Figure 4a, pointers are allocated from one end of the block and parameters at the other. When the block is full the two meet in the middle. In Figure 4b, the parameters and pointers are interleaved and the allocation block is filled from beginning to end. A further variation as shown in Figure 4c is more suitable for allocation blocks larger than one page. It attempts to keep object pointers in the same data block as the parameter data to which they

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point but at the expense of some wasted space in the object pointer blocks.

Because allocation blocks are associated with macro-tiles and each macro-tile contains a number of tiles,  
5 there will be multiple linked lists of object pointer blocks within each allocation block.

Where a scene consists of large objects and the macro-tiles each contain a large number of tiles, it may be found that a large amount of space in the allocation  
10 blocks is wasted by pointer blocks that are mostly empty, and whose pointers all point to the same objects.

Figure 5 shows a scheme where a single list is used with a tile mask indicating in which of the tiles of the macro-tile the object is visible. Strip masks are  
15 separate from object pointers and are packed. The step of fetching the image synthesis processor parameters can skip to the relevant strip marks by counting the number of bits set in the tile mask.

In all the allocation schemes described above it is  
20 possible to compress object pointers by representing them using the appropriate number of least significant bits, since the pointer is always pointing to parameter data within the same allocation block. Pointers to objects outside the block (e.g., in a global list) would need to  
25 have the most significant bits of the address supplied as well. This could be by using a larger pointer.

A very large triangle or strip, i.e., one that crosses many macro-tiles can cause a problem for the scheme described above. This is because the data is  
30 replicated in many macro-tiles and thus uses a large amount of memory. One solution to this problem is to create a global list in which large objects are stored. References to these objects are then written into each macro-tile's pointer list in the normal way to ensure that  
35 the order of objects is preserved.

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The object could be deemed to be large when it is visible in a number of macro-tiles greater than some threshold value. This threshold could be chosen to achieve an optimal trade-off between parameter  
5 replication, memory used by the global list and recycling of parameter memory. As the parameter data in the global list may be referenced in the pointer lists of many macro-tiles it remains in memory for a relatively long period of time. It is therefore important that the global list is  
10 not allowed to grow so large as to adversely affect the operation of the macro-tiling. A crude solution would be to render all macro-tiles when the size of the global list exceeds a threshold. This would allow all allocation blocks associated with a global list to be returned to the  
15 free store. A more elaborate scheme could employ reference counting, thereby allowing global list allocation blocks to be released as soon as the macro-tiles that reference them have been rendered.

The choice of which macro-tile to render next is  
20 generally determined by the maximum amount of memory which will be released back to the free store. This increases efficiency by ensuring that macro-tiles are able to develop a reasonable amount of complexity between renders and also reduces the total number of z/frame buffer load  
25 and store operations that are required.

When the display list contains blocks associated with macro-tiles for a number of frames, it is essential that all tiles belonging to one frame are rendered completely before rendering any tile from the next.

30 It is easy to imagine where a busy macro-tile is being rendered and, at the same time, the tiling accelerator is writing more data into the same macro-tile. This could arise where a small area of the screen contains a particularly detailed object. In such a situation it  
35 may make sense to weight the choice of the next macro-tile to render in favour of repeating the same one. This would

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allow z load and store to be omitted for at least one tile in the macro-tile or for more than one if a small on-chip cache is present. For the greatest benefit it must be possible to render the tiles in the macro-tile in an 5 arbitrary order.

When the global list becomes uncomfortably large, an extension of the reference counting scheme described above would allow a macro-tile to be chosen for rendering that will release the largest possible number of global list 10 allocation blocks.

An alternative implementation would be to use a hierachal macro-tile system using nested macro-tiles of progressively increasing size. This aim is to reduce replication of parameter data by selecting an appropriate 15 level of the hierarchy for storage, depending on the number of tiles in which an object appears. Object pointers would be stored at the lowest level only in order to preserve the order of the objects.

The macro-tiled memory management technique described 20 above reduces the bandwidth requirements of the system considerably, but cannot eliminate z/frame buffer load and store entirely. It should also be noted that the stored z information occupies additional memory space. Compression of the z and frame buffer data reduces memory bandwidth 25 and storage requirements still further.

A variety of compression techniques can be used that to reduce the amount of space occupied by the saved data. The efficiencies of different compression methods are affected by the nature of the data being compressed, such 30 that a single scheme is unlikely to offer effective compression in all situations. Therefore, a hierarchical system is proposed, in which the system will fall back to an alternative method of compression if the current scheme is not appropriate to the current data set.

35 Alternatively, any one of the proposed methods might be

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used in isolation, at the risk of offering poor data compression (or even expansion) in some cases.

1) **Storage of face plane equations of surfaces for z compression**

5 The z values in a tile are comprised of the depths of the triangles that are visible at each pixel. Although there may be many triangles processed for each tile, it is often the case that only a small number of triangles are visible, and therefore contributing to the depth values.

10 In the case of the z-clear polygons that occur at the beginning of most images, one polygon will define the initial z state for the entire tile.

15 For a given polygon, the z information is defined by the three plane parameters, A, B, and C, calculated by the ISP. The parameters are used in the equation depth  
= Ax + By + C, where x and y are the position of the pixel in question, with (0,0) at the top left corner of the tile.

20 Storage of the A, B and C parameters requires 12 bytes of data per triangle. An additional bit map value is stored per-pixel to select between different sets of parameters. An example where the z depths are defined by four polygons is shown in Figure 6.

25 Compressing the data requires knowing how many polygons contribute to the z values, and the ability to recall the plane parameters for those polygons. This data could be computed from the stored object identity tags at the point where the data is output to the TSP. In the case where more than eight polygons contribute to the 30 depths, the system would fall back to one of the alternative schemes mentioned below.

Compression rates for different numbers of triangles contributing to the depth information in a rectangular tile of 32 x 16 pixels are as follows:

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Num Polys	ISP Data Size	Bit map data size	Total data size
1	12 bytes	0	12 bytes
2	24 bytes	64 bytes	88 bytes
3-4	48 bytes	128 bytes	176 bytes
5	96 bytes	256 bytes	352 bytes

The raw floating point z data would require 2048 bytes. The method can therefore be seen to give a considerable compression ratio of between 5 and 128 times.

Reloading these depth values would require 10 calculations similar to those that the ISP performs when processing a triangle. The depth values computed in this way would be written into the depth buffer according to the bit map data in order to reconstruct the original set of values.

15 The example above allows the Z depth to be defined by between one and eight triangles, although other ranges could be used. If the number of triangles falls outside this range, the system can fall back to an alternative system, described below.

20 2) **Run length encoding for Z compression**

Run length encoding is commonly used when data contains large numbers of consecutive items with the same value. Numbers are stored in pairs, so that, for example, the encoding 8:0.5, 24:0.8 would indicate a row of pixels 25 where the first eight had a depth value of 0.5, and the following 24, presumably belonging to a different triangle, have a depth value of 0.8.

An alternative type of run length encoding will usually prove more effective for encoding depth information, where it is quite likely that triangles are not "flat on" and therefore have depth values that change uniformly across the tile. This situation is shown in 30 Figure 7. Since triangles are planar, it is found that

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the "delta" values (the differences in depth between one pixel and the next) are constant. In fact, when moving across the tile in the x direction, the delta value is equal to the ISP's "A" parameter for that polygon. Run length encoding the x delta values along lines of the tile (constant y) gives a compression ratio of approximately 2 times with typical data (from experimental results).

Run length encoding (of values rather than deltas) is also highly appropriate for stencil and "tag" (the identity of the object at a particular pixel position) values, which may need to be stored along with the depth information to fully record the state of the ISP.

A disadvantage of run length encoding is that it is possible to have a situation where the data size actually expands. This would occur, for example, where no adjacent pixels are identical. The compressed data could actually double in size, since it would be necessary to store a counter indicating that each value occurs only once. In this case, the Z compression system would fall back to storing uncompressed z values.

### 3) Frame buffer compression

The frame buffer memory is read directly by the hardware that produces the video image, and therefore the final output cannot be compressed. However, if data is stored and loaded a number of times in the process of composing the image, memory bandwidth can be conserved by compressing the intermediate data. Standard image compression techniques, including Run Length Encoding, J-PEG, Wavelet, or Vector Quantisation (VQ) may be used.

### 30 4) Write Z only when changed, read TSP only on demand

A final optimisation may make it possible to avoid some z stores and frame buffer loads altogether.

A "dirty" flag indicates that data has been modified since it was last read. In the case of z buffer

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load/store, the dirty flag would be cleared when a z load occurs, and set when the z data is modified by the ISP. When a z store is requested, it is only necessary to actually save the data if the dirty bit is set.

5       A similar optimisation can be applied to frame buffer loads and stores. It is only necessary to load pixels from the frame buffer when they are required by a particular blending operation, and this situation may not always arise. Similarly, a dirty flag would indicate 10 pixels or groups of pixels which have been modified, and only those pixels would be transferred by a frame buffer store operation.

5)      **Allowing the application to access the "z-buffer" if it wants to**

15       Some rendering systems such as the Imagination Technologies Power Vr System do not normally need to maintain a z buffer for the entire frame. This saves memory, and bandwidth. Some applications, however, expect to see a z buffer, and attempt to manipulate it themselves 20 in order to achieve special graphical effects. Although the data stored by the z buffer store operations is not a z buffer in the conventional sense, it is possible to make it appear as such to the application, by taking care over the layout of data in memory. If necessary additional z 25 buffer store operations can be performed to ensure that the saved z values reflect the state of the imaginary z buffer at the appropriate times.

30       A conventional z buffer contains raw, uncompressed z data. Clearly, any application that attempted to read a z buffer compressed using the methods described above would be unable to interpret it correctly. It is essential therefore, that there is a facility to either switch off the compression for those applications that require it, or to provide additional hardware that presents a "virtual" z

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buffer to the application, and performs compression and decompression transparently.

Diagrams illustrating an embodiment of the invention now follow. Figure 8 shows the block diagram of the type of system to which the invention is applied. This comprises a slightly amplified version of figure 1 and shows a tile accelerator 2 performing tiling operations which are supplied to a display list memory 4. This in turn supplies data to an image synthesis processor 6 for performing ray/surface intersection tests. After this data is supplied to a texture and shading processor 8 which applies texture and shading data, from a texture in memory 9 before storing the textured image data in frame buffer memory 11. This apparatus operates in accordance with the description given earlier with relation to figure 1.

Figure 9 shows this system figure 8 modified by circuitry to perform a Z/frame buffer load and store operation. In this, a Z buffer memory 16 is linked to the image synthesis processor 6 via a z compression/decompression unit 18. This comes into operation when the system is rendering a complex scene and the display list memory is not large enough to contain all the surfaces which need to be processed for a particular tile. This process has been described previously. However, when operating using the system of figure 9, the display list will be loaded with data by the tile accelerator for all the tiles until it is substantially full. This may, however, only represent a portion of the initial data. The image is rendered one tile at a time by the image synthesis processor 6. The output data for each tile is provided to the texture and shading processor 8 which uses data from the texture memory 9 to texture the tile and supply it to the frame buffer memory 11.

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At the same time, because the image data was incomplete, the result from the image synthesis processor 6 is stored to z buffer memory 16 via the compression/decompression unit 18 for temporary storage. The rendering of the remaining tiles then continues with the incomplete image data until all the tiles have been rendered and stored in frame buffer memory and in the z buffer memory 16.

The first part of the display list is then discarded and the additional image data read into it. As processing is performed for each tile in turn by the image synthesis processor 6 the relevant portion of data from the z buffer memory 16 is loaded via the z compression/decompression unit 18 so that it can be combined with the new image data from the display list memory 4. The new data for each tile in turn is then fed to the texture and shading processor 8 which combines it with data from texture memory 9 before supplying it to the frame buffer 11.

This process continues for all the tiles in the scene and until all the image data has been rendered.

Thus, it can be seen that the z buffer memory fills a temporary store which enables a smaller display list memory to be used than would be necessary for rendering particularly complex scenes. The compression/decompression unit 18 is optional but its use enables a smaller z buffer memory to be employed.

A frame buffer compression/decompression unit 20 is provided as an additional link between the texture and shading processor and the frame buffer memory. Preferably, this is used for temporary storage of incomplete image data in the frame buffer memory and for feeding back that data when additional data is provided from the image synthesis processor 6 for a tile which has to be combined with the data already

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textured and shaded for that tile. This compression/decompression unit is of course optional.

In figure 10 the memory management system used by the tiling accelerator is illustrated. This should be 5 read in combination with the description of figure 3. At step 30, the region headers are initialised and step 32 the system waits for object data to be input for the regions. At 34 tiles and macro tiles are allocated as 10 illustrated in figure 3 and at 36 its determination is made as to whether or not any new memory blocks are required. If additional memory blocks are not required then object data in macro tiles is stored in memory blocks as previously allocated by the system whilst at 15 40 the determination is made as to whether or not the last object in the frame has been reached in the allocation of object data to macro tiles and memory. At 42 determination is made as whether or not any unrendered macro tiles exist for the frame if they do then at Step 44 a macro tile is selected for rendering 20 and the rendering commenced at 46 before a determination is made at 48 as to whether or not additional objects are required to be stored and rendered. If the answer is no then at 42 a 25 determination is made as to whether another tile is to be rendered and if no further macro tiles exist, a determination is made at 50 as to whether another frame or data is to be entered. If it is, the system returns to the top of the flow diagram.. If not this process terminates. If the determination at 42 is yes then 30 control flows to fig 6 for new blocks from memory to be loaded.

If at step 36 a determination is made that additional memory is required then at step 52 a determination is made as to whether or not the memory 35 fill threshold has already been exceeded. If it is not

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then at 54 new memory blocks are claimed from the free store at 54 and are used at 38 to store object data in macro tiles before proceeding to step 40 as before. If the memory fill threshold has been exceeded then the  
5 process skips to step 44 where macro tiles are rendered. If this route is taken at step 48 the determination will be that the system is waiting to store an object. In which case the process will activate step 56 which will wait until memory blocks  
10 are available before they can be claimed at step 54 for storing additional objects in macro tiles at step 38.

Figure 11 illustrates how memory blocks are freed and returned to store for future allocation by the tile accelerator. At 80, the system is activated to wait for a  
15 signal that a partial render has been completed. When this is received, memory blocks are returned to store at 82 and the system waits for the end of the next partial render.

Because tiling and rendering occur in parallel, this freeing up of memory blocks is illustrated separately in  
20 figure 10, at 46 a render is commenced by sending a signal to the ISP. It doesn't wait for it to complete, because the tile accelerator can be performing more tiling work in that time. This is why there is a threshold (e.g. 79%) at which rendering of macro tiles commences. This leaves the  
25 unfilled portion of memory for the tile accelerator to work with.

The system of figure 11 waits for the ISP to indicate that a partial render is complete because it doesn't know the stage in the cycle at which the tile accelerator is  
30 and doesn't wish to interrupt it. Figure 11 simply releases what memory it can, such that when steps 56 and 54 in figure 10 are reached. There is a good chance that the memory will be immediately available for use. It is necessary sometimes to wait at 56 because memory will not  
35 always be available. This may occur with complex images

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and it is then necessary to wait for memory to become available.

Figure 12 shows the ISP 6 and display list memory 4 at figures 8 and 9 but with the tile accelerator 2 shown in more detail. Input data 90 passes to a tiling unit 92 and this data then passes to a macro-tiling unit 94. Output data 95 from this passes to the display list memory 4 and also to a display list memory manager 96. The memory manager 96 is in communication with the free store list 98 and with the display list 45 to indicate that the memory is e.g. 75% full and in response to this sends a start render signal to the ISP6. When this is complete an end render signal is sent to the memory manager 96 which returns the memory now made available to the free store list 98 for use by further macro tiles. The memory manager continues to receive macro-tile data, whilst previous macro-tiles are being rendered, and allocates memory from the free store list to the objects in these as required.

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CLAIMS:

1. A method for generating 3-dimensional computer images comprising the steps of:

5 a) subdividing the image into a plurality of rectangular areas;

b) loading object data for each rectangular area into a display list memory until that memory is substantially full;

10 c) deriving image data and shading data for each picture element of each rectangular area from the object data;

d) storing the image data and the shading data;

e) loading further object data into the display 15 list memory to replace the existing contents;

f) retrieving the stored image data and shading data;

g) deriving additional image data and shading data for each picture element of each rectangular area from the 20 new object data and the previously derived image data and shading data;

h) repeating steps d), e), f) and g) until there is no further object data to load to the display list memory; and

25 i) providing the shading data for display.

2. A method according to claim 1 in which the image data comprises object identification data and depth data.

30 3. A method according to claim 1 or 2 including the steps of compressing the image data prior to step d) and decompressing the compressed image data prior to step g).

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4. Apparatus for generating 3-dimensional computer images comprising:

- a) means for subdividing the image into a plurality of rectangular areas;
- 5 b) means for loading object data for each rectangular area into a display list memory until the memory is substantially full;
- c) means for deriving image data and shading data for each picture element of each rectangular area from the object data;
- 10 d) means for storing the image data and shading data for each rectangular area;
- e) means for loading further object data into the display list memory to reduce the existing contents;
- 15 f) means for retrieving the stored image data and shading data;
- g) means for deriving further image data shading data for each picture element of each rectangular area from the new object data and the stored image data and shading data;
- 20 h) means for causing features d), e), f) and g) to repeatedly perform the functions until there is no further object data to load to the display list memory; and
- 25 I) providing the shading data for display.

5. Apparatus according to claim 4 in which the image data comprises object identification and depth data.

6. Apparatus according to claim 4 or 5 including means to compress the image data before it is stored and means to decompress the compressed image data after it is retrieved.

7. A memory management system for use with systems for generating 3-dimensional computer images comprising means for subdividing the image data into a plurality of

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substantially rectangular areas, means for storing data pertaining to surfaces making up the image in a display list memory, means for allocating at least one block of storage from the display list memory to each rectangular area and means for storing in that block of memory data pertaining to surfaces which intersect that rectangular area, means for supplying data for each rectangular area from the display list to a means for deriving shading data for each picture element of the rectangular area, and frame store means for storing the shading data for display characterised in that each rectangular area comprises a plurality of smaller rectangular areas and the means for deriving shading data derives the data for each smaller rectangular area in turn.

8. A memory management system according to claim 7 in which the means for allocating blocks of storage from the display list determines when a predetermined number of blocks have been used and, in dependence on the determination, causes the means for supplying data to the means for deriving shading data to commence operation, thereby releasing blocks of storage for further object data.

9. A memory management system according to claims 7 or 8 in which the image data comprises a sequence of frames of data.

10. A method for managing memory for a system for generating 3-dimensional computer images comprising the steps of subdividing the image into a plurality of rectangular areas, storing data pertaining to surfaces in the image which intersect each rectangular area in a display list memory, allocating at least one block of the display list memory to each rectangular area, storing in that block data pertaining to surfaces intersecting the respective rectangular area, supplying data for each

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rectangular area to a shading means whereby shading data  
is derived from each picture element making up the  
rectangular area, and storing the shading data for display  
characterised in that the step of subdividing the image  
5 further comprises subdividing each rectangular area into a  
plurality of smaller rectangular areas and the shading  
means shades each smaller rectangular area in turn.

10 11. A method for managing memory according to claim  
including the step of determining when a predetermined  
number of blocks of the display list memory have been  
allocated to rectangular areas, and commences the supply  
of data to the shading means in dependence on the  
determination, thereby releasing blocks of storage for  
further object data.

15 12. A memory management system for use with systems  
for generating 3-dimensional computer images comprising  
means for subdividing the image data into a plurality of  
substantially rectangular areas, means for storing data  
pertaining to surfaces making up the image in a display  
list memory, means for allocating at least one block of  
storage from the display list memory to each rectangular  
area, means for storing in that block of memory data  
pertaining to surfaces which intersect that rectangular  
area, means for supplying data for each rectangular area  
20 from the display list to a means for deriving shading data  
for each picture element of the rectangular area, and  
frame store means for storing the shading data for  
display, characterised in that the means for allocating  
blocks of storage from the display list memory determines  
when a predetermined number of blocks have been used and,  
25 in dependence on the determination, causes the means for  
supplying data to the means for deriving shading data to  
commence operation, thereby releasing blocks of storage  
for further rectangular areas.

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13. A method for managing memory for a system for generating 3-dimensional computer images comprising the steps of subdividing the image into a plurality of rectangular areas, storing data pertaining to surfaces in  
5 the image which intersect each rectangular area in a display list memory, allocating at least one block of the display list memory to each rectangular area, storing in that block data pertaining to surfaces intersecting the respective rectangular area, supplying data for each  
10 rectangular area to a shading means whereby shading data is derived from each picture element making up the rectangular area, and storing the shading data for display, characterised by the step of determining when a predetermined number of blocks of the display list memory  
15 have been allocated to rectangular areas, and commencing the step of supplying data to the shading means in dependence on the determination, thereby releasing blocks of storage for further object data.

14. A memory management system for use with systems for shading 3-dimensional computer generated images substantially as herein described.  
20

15. A method for managing memory for a system for shading 3-dimensional computer generated images substantially as herein described.

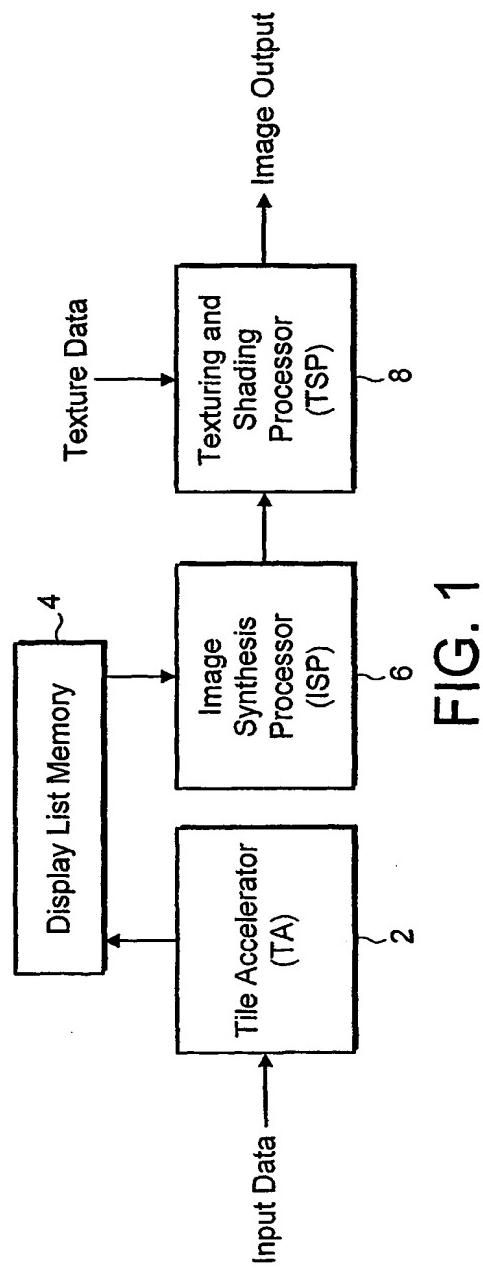


FIG. 1

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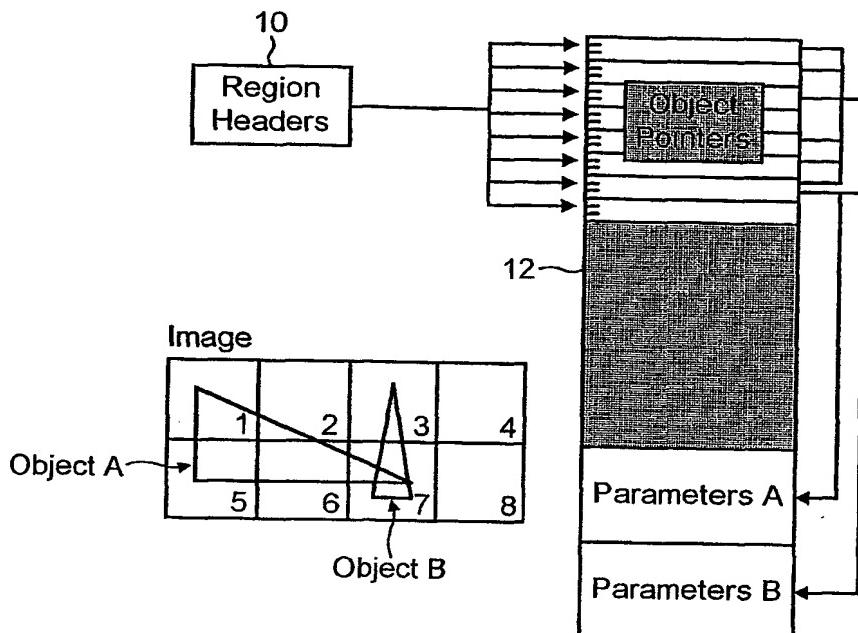


FIG. 2

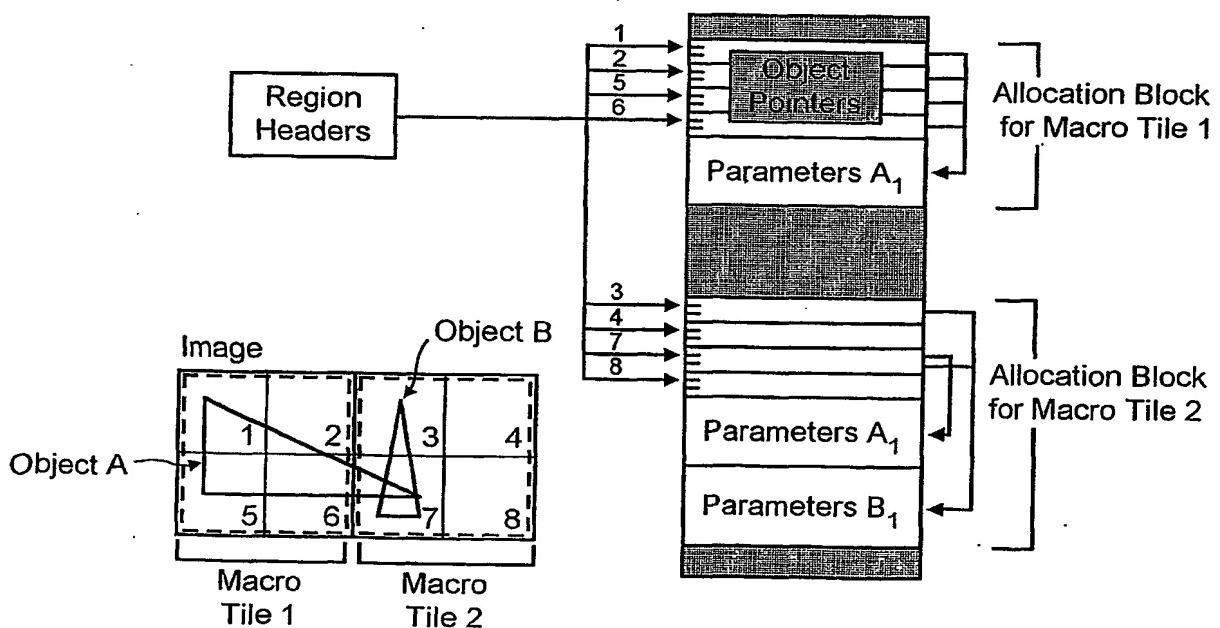


FIG. 3

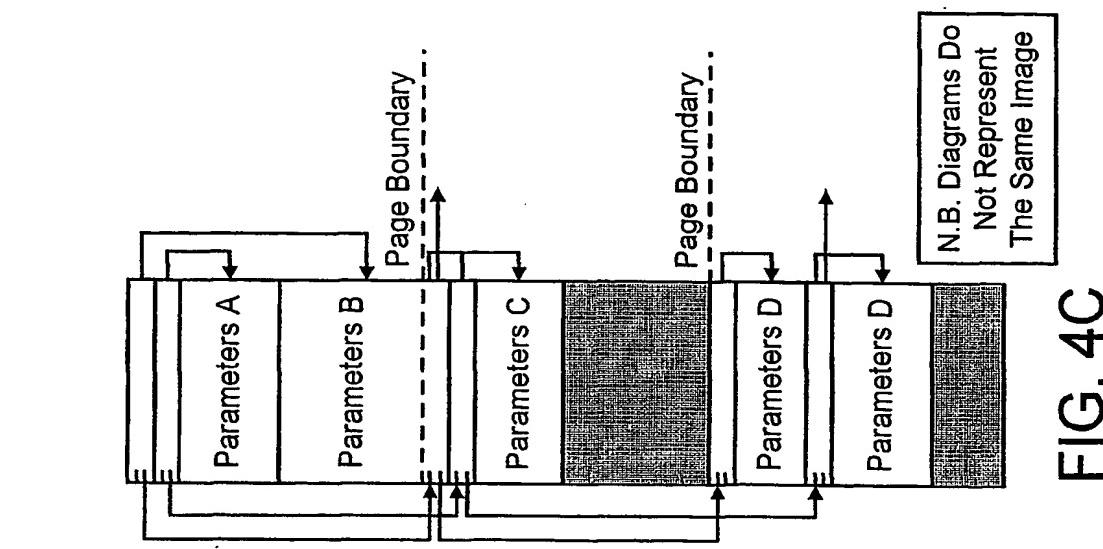


FIG. 4C

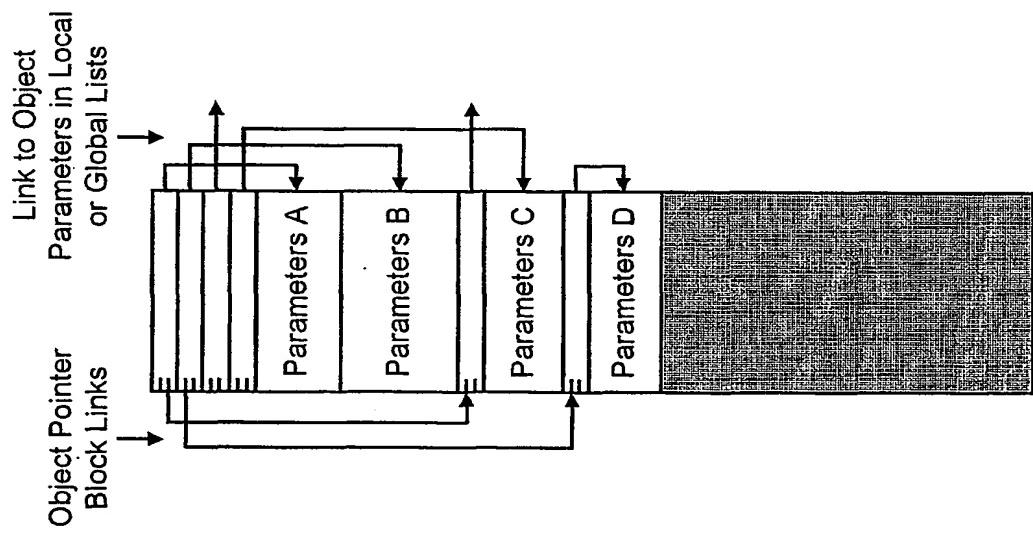


FIG. 4B

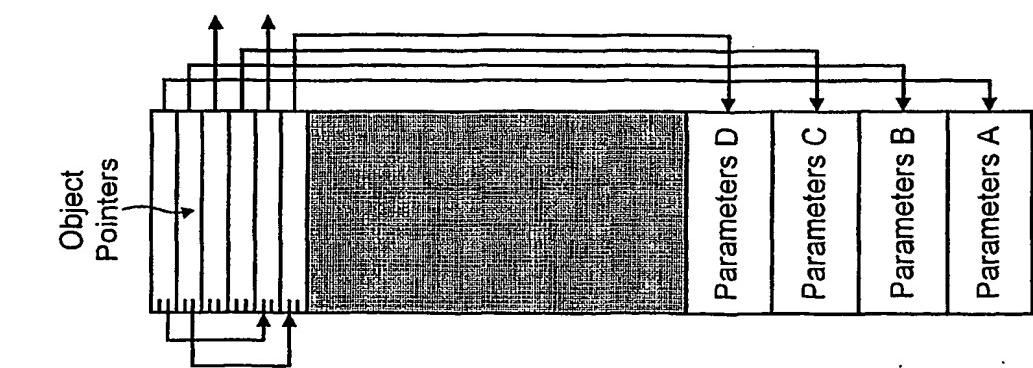


FIG. 4A

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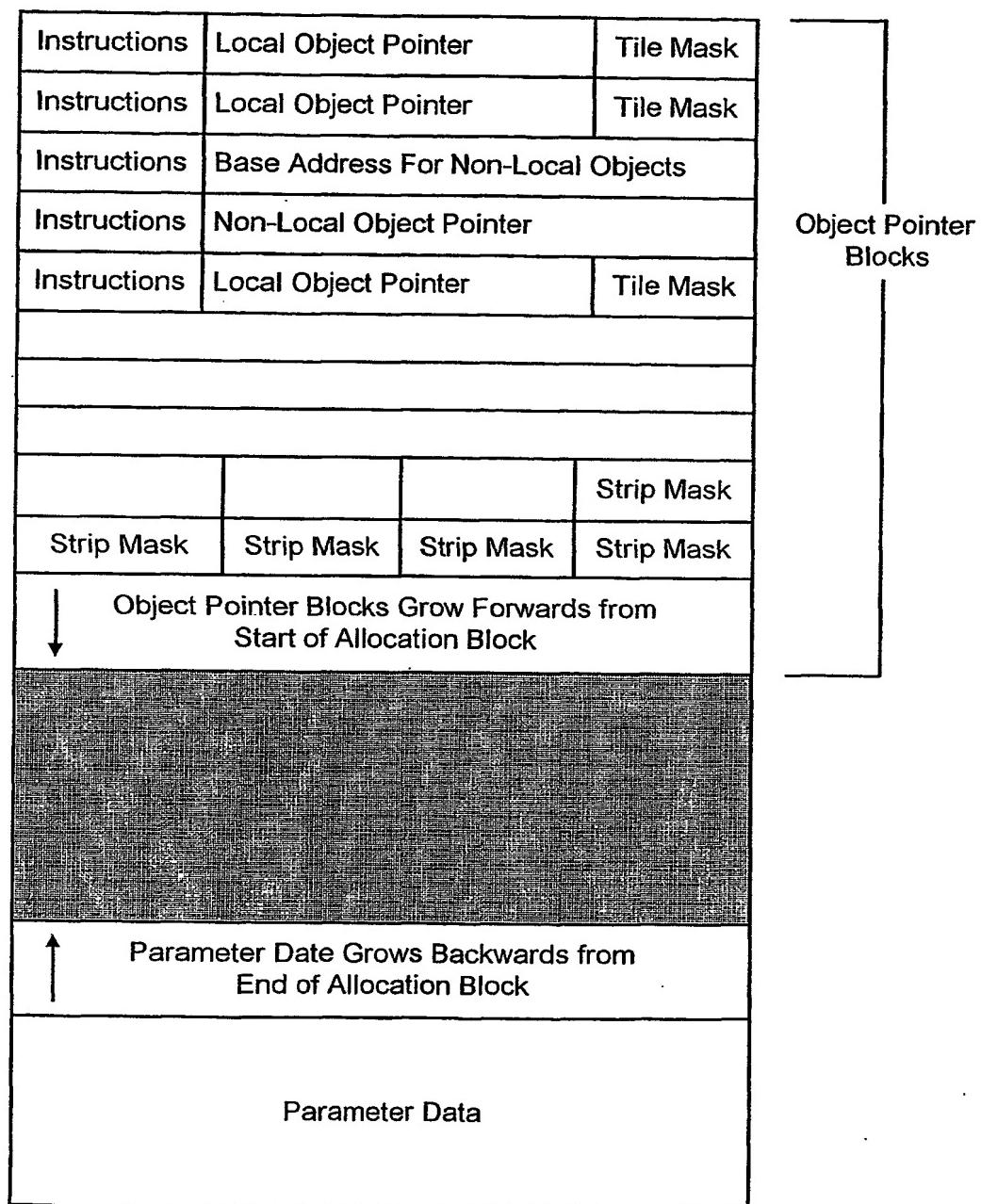
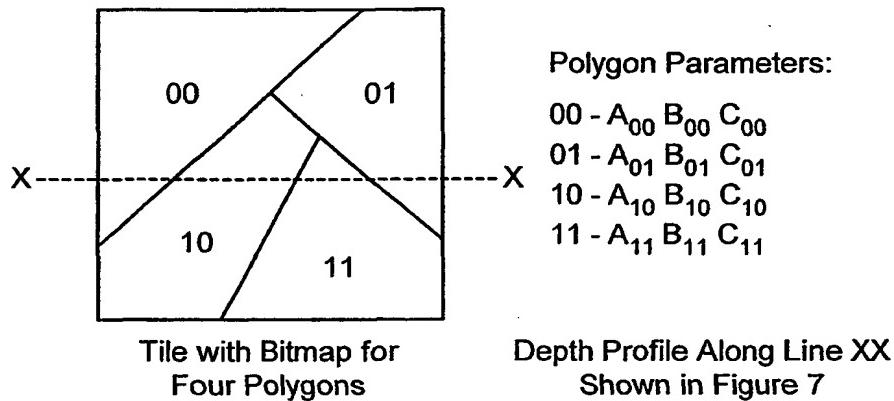
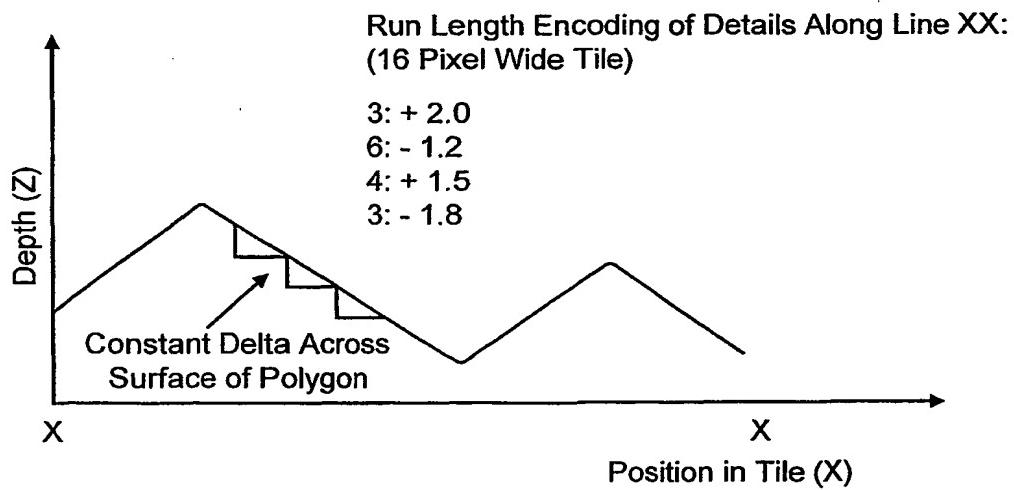


FIG .5

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**FIG. 6****FIG. 7**

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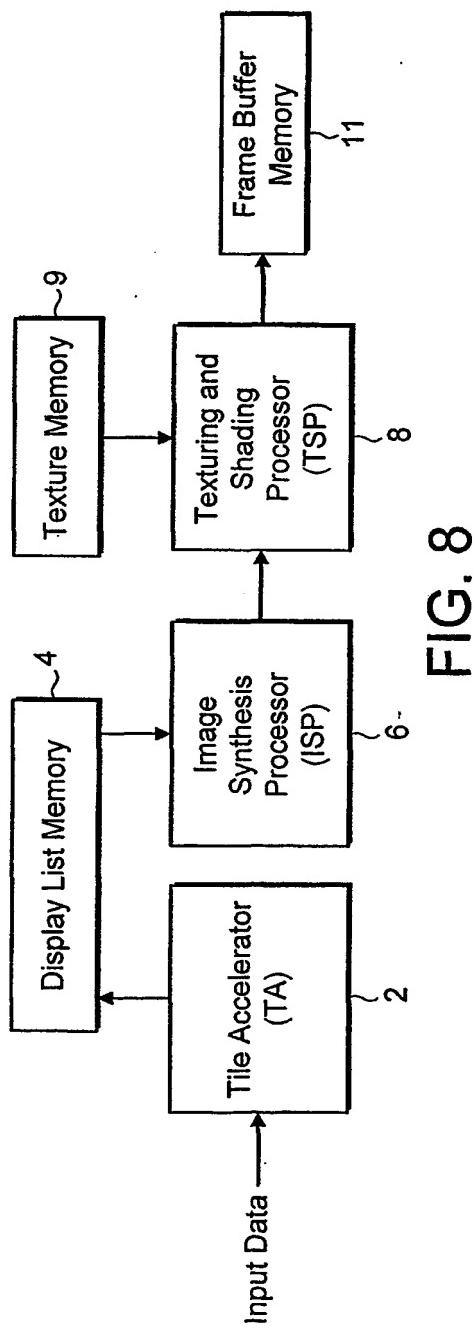


FIG. 8

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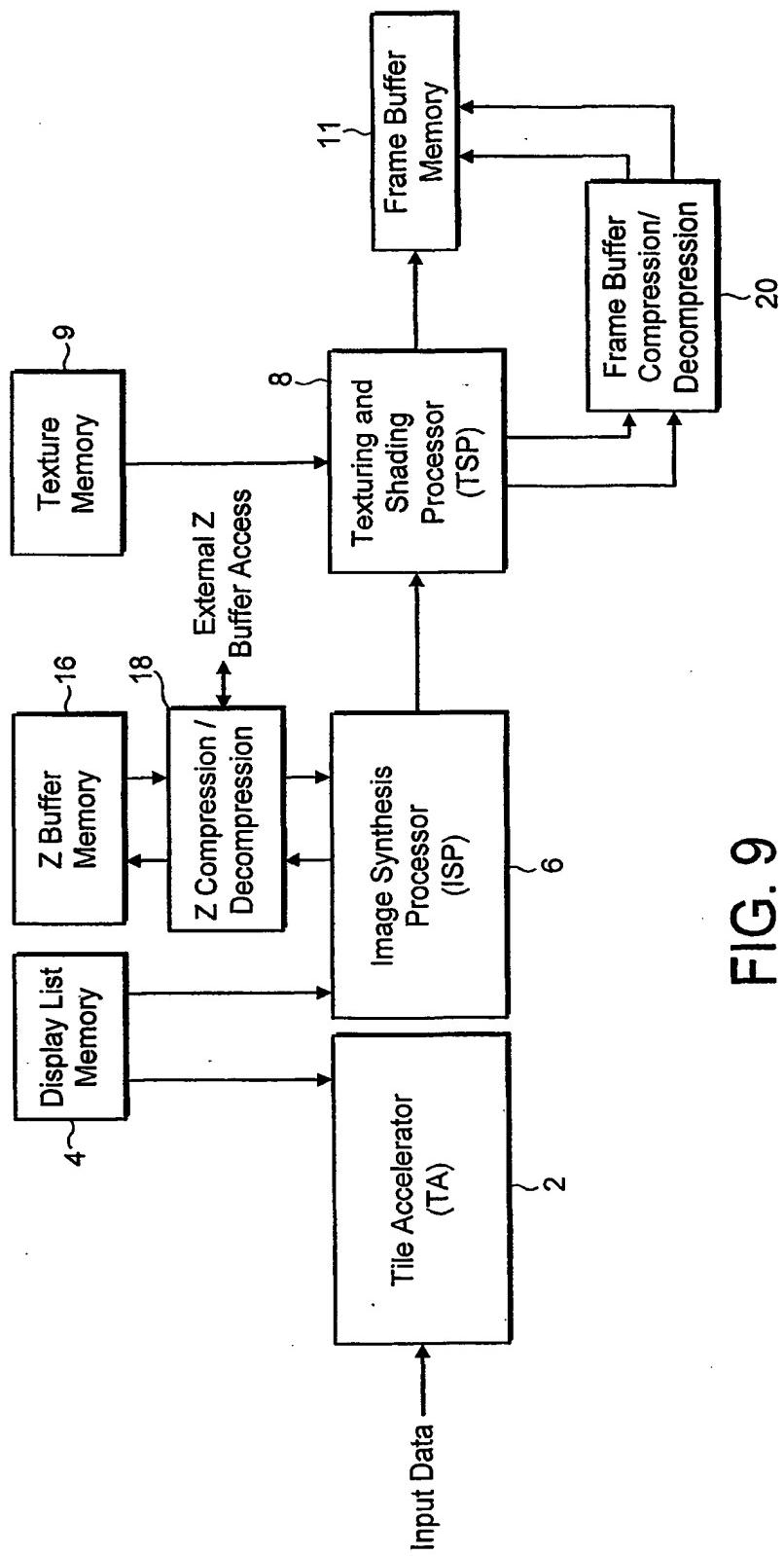


FIG. 9

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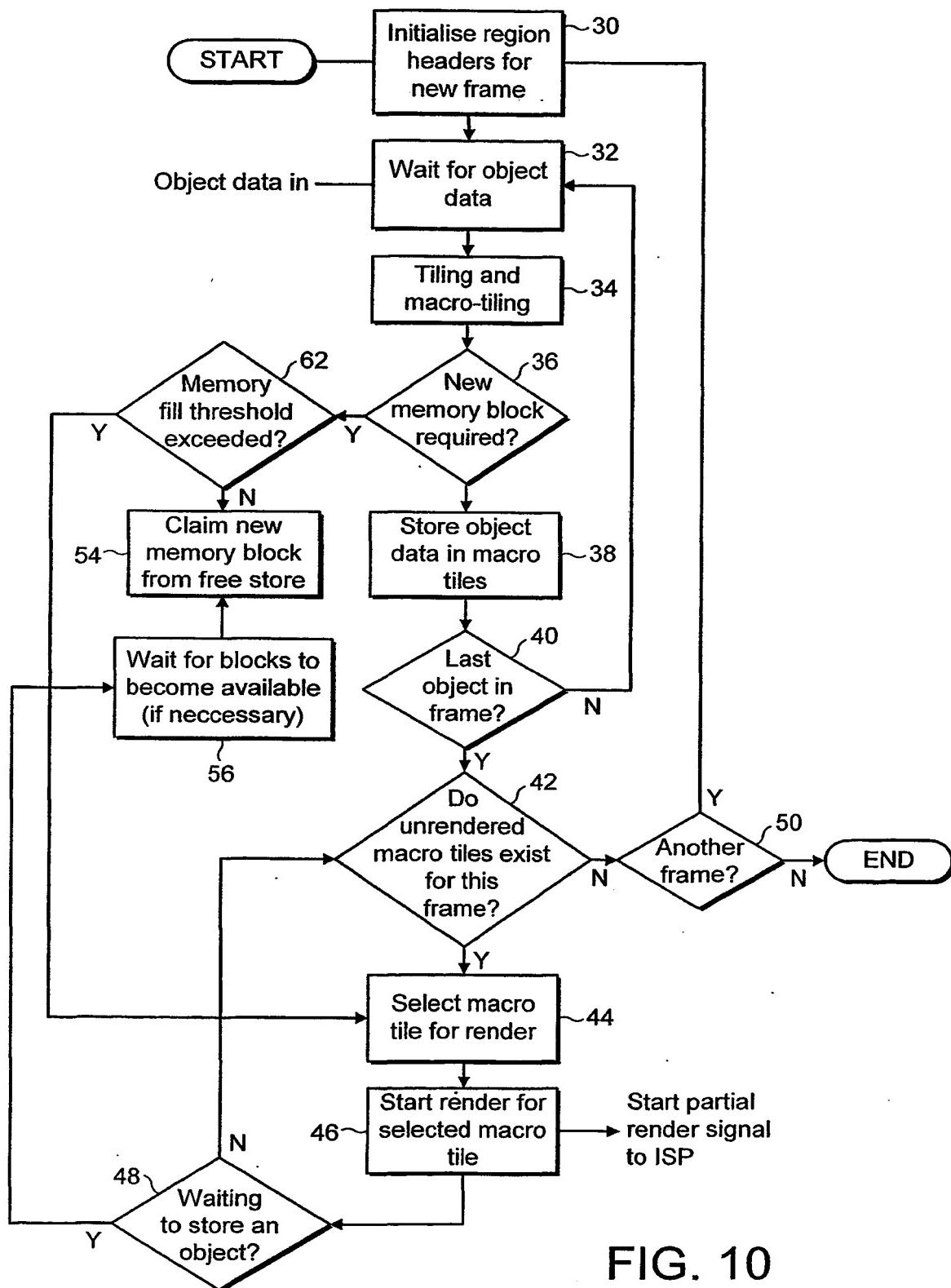


FIG. 10

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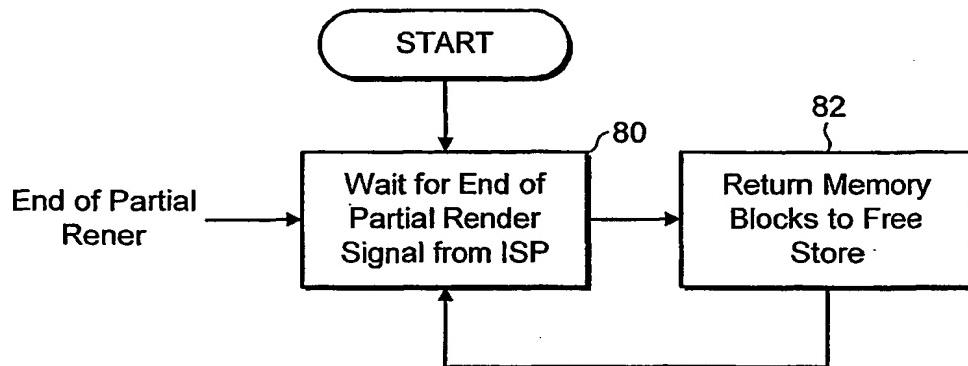


FIG. 11

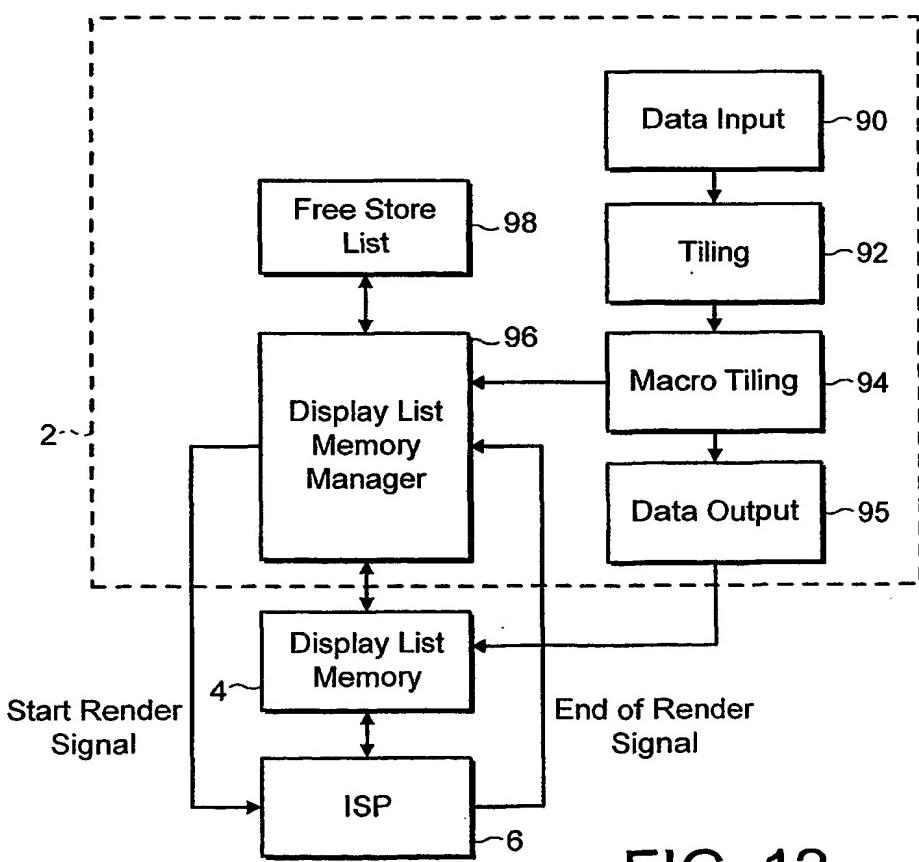


FIG. 12

**INTERNATIONAL SEARCH REPORT**

Intern	Application No
PCT/GB 01/02536	

**A. CLASSIFICATION OF SUBJECT MATTER**  
IPC 7 G06T15/00

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)  
IPC 7 G06T

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the International search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, INSPEC, PAJ

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 886 701 A (POWELL III WILLIAM CHAMBERS ET AL) 23 March 1999 (1999-03-23) abstract; figures 9,20 column 5, line 25 -column 6, line 16 column 8, line 11 - line 62 column 9, line 36 -column 10, line 37 column 16, line 13 - line 60 column 61, line 61 -column 63, line 20	1-13
A	US 5 392 385 A (EVANGELISTI CARLO J ET AL) 21 February 1995 (1995-02-21) figures 2,7 column 3, line 7 -column 5, line 19	1
A	US 5 522 018 A (TAKEDA MASAKI ET AL) 28 May 1996 (1996-05-28) figure 9	2
	---	-/-

Further documents are listed in the continuation of box C.

Patent family members are listed in annex.

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- \*O\* document referring to an oral disclosure, use, exhibition or other means
- \*P\* document published prior to the international filing date but later than the priority date claimed

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- \*Y\* document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
- \*&\* document member of the same patent family

Date of the actual completion of the international search

5 September 2001

Date of mailing of the International search report

12/09/2001

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## INTERNATIONAL SEARCH REPORT

Inten | Application No  
PCT/GB 01/02536

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